Effect of Longitudinal Variation of Vocal Fold Inner Layer Thickness on Fluid-Structure Interaction During Voice Production

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A three-dimensional fluid-structure interaction computational model was used to investigate the effect of the longitudinal variation of vocal fold inner layer thickness on voice production. The computational model coupled a finite element method based continuum vocal fold model and a Navier–Stokes equation based incompressible flow model. Four vocal fold models, one with constant layer thickness and the others with different degrees of layer thickness variation in the longitudinal direction, were studied. It was found that the varied thickness resulted in up to 24% stiffness reduction at the middle and up to 47% stiffness increase near the anterior and posterior ends of the vocal fold; however, the average stiffness was not affected. The fluid-structure interaction simulations on the four models showed that the thickness variation did not affect vibration amplitude, glottal flow rate, and the waveform related parameters. However, it increased glottal angles at the middle of the vocal fold, suggesting that vocal fold vibration amplitude was determined by the average stiffness of the vocal fold, while the glottal angle was determined by the local stiffness. The models with longitudinal variation of layer thickness consumed less energy during the vibrations compared with the constant layer thickness one.

[DOI: 10.1115/1.4041045]

Introduction

The primary sound source of voice is the glottal flow pulse generated by the vibration of vocal folds. Vocal fold vibration controls the waveform of the glottal flow pulse, therefore directly affects the spectrum of sound source. As the vibratory dynamics of the vocal fold is directly determined by its geometry and material properties, one of the important goals in voice production research is to understand how vocal fold properties affect the interplay between glottal flow and vocal fold vibration and how they eventually affect voice outcomes. Such knowledge can help surgeons improve diagnosis and treatment techniques for voice disorders. For example, it can be used to predict/estimate the impact of tissue damage and assist the development of engineering vocal fold tissue and prosthesis for replacing damaged tissue [1–3].

The human vocal fold is a layered structure, consisting of an outmost epithelium layer, a soft tissue layer of the lamina propria, and an inner muscular layer. Based on their mechanical properties, these tissues are often regrouped into three mechanical layers: a cover layer consisting of the epithelium and superficial layer of the lamina propria, a ligament layer consisting of the intermediate and deep layers of the lamina propria, and a body layer consisting of the muscle [4]. Intensive effort has been devoted to studying the effect of inner layer structure and properties on vocal fold dynamics and voices. For example, it was revealed that a multilayer synthetic vocal fold model which includes the epithelium, superficial lamina propria, intermediate and deep lamina propria, and muscle layers can improve the vibratory characteristics of vocal fold over homogeneous and simple two-layer models [5]. It was demonstrated in synthetic models that embedding fibers in the cover layer or adding a stiffer

epithelium layer could significantly improve glottal closure [6]. The effect of inner layer stiffness on vocal fold vibration and phonation onset was investigated in a number of computational models [7–11]. It was found that changing inner layer stiffness could significantly affect vocal fold vibration pattern and amplitude, threshold pressure, and onset frequency. Cook et al. [12] and Xue et al. [13] used continuum vocal fold models to systematically study the sensitivity of eigenfrequencies and eigenmodes of vocal fold to its inner layers' geometry and material properties, and they both found that inner layer stiffness could significantly affect these quantities.

In the human vocal fold, the thickness of each layer is known to vary along the longitudinal direction [4]. Usually, the stiffer ligament layer is thicker at the sites of attachment at the anterior commissure and the vocal process of the arytenoid to withstand the massive stress of vocal fold action. The softer cover layer is thicker at the middle to provide a cushion for vocal fold collision [14]. Figure 1 shows the averaged thickness of the cover and ligament layers at different longitudinal positions of five male vocal fold samples measured by Hirano et al. [4]. The square and diamond symbols represent the original measurements of the ligament and cover, respectively, and the curves are the fourth-order polynomial curves fitting the data. According to the data, the variation of the thickness in the longitudinal direction is up to 57% and 43% for the cover and ligament, respectively, about their average values. These are relatively large variations which could have a significant impact on stiffness distribution on the vocal fold. Based upon the aforementioned findings that inner layer stiffness can significantly affect vocal fold vibration amplitude and pattern, the longitudinal variation of thickness might affect vocal fold vibration through its effect on stiffness. Bhattacharya et al. [9] have computationally investigated the influence of longitudinal stiffness variation of the vocal fold on vibration by changing the elastic modulus. It was found that the stiffness variation could affect the fundamental frequency and flow rate and caused anterior–posterior asymmetry and a wave motion in the

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Manuscript received January 24, 2018; final manuscript received July 24, 2018; published online September 25, 2018. Assoc. Editor: Ching-Long Lin.

Fig. 1 The averaged thickness of the cover and ligament layers of five male vocal fold samples measured by [4]. The square and diamond symbols represent the original measurement of ligament layer and cover layer, respectively. Fourth-order polynomial curves are applied to fit the data: $y = 5.92x^4 - 12.16x^3 + 11.16x^2 - 4.84x + 1.51$ for the ligament and $y = 5.10x^4 - 9.29x^3 + 3.60x^2 + 0.62x + 0.15$ for the cover, where x is the nondimensional longitudinal position and y is the layer thickness (mm). 1.11 mm and 0.33 mm are the averaged layer thicknesses for the ligament and cover, respectively.

longitudinal direction. However, in that study, the vocal fold was modeled as a one-layer isotropic material. Vocal fold is anisotropic and it was reported that the anisotropy could significantly suppress the wave motion in the longitudinal direction [10]. Moreover, vocal fold is prestressed in the longitudinal direction during posturing. This condition will stiffen the vocal fold and further suppress the wave motion in the longitudinal direction. However, this feature was not modeled in Ref. [9]. Therefore, the model may have overpredicted the wave motion in the longitudinal direction. In fact, it was observed in the experiment that vocal fold vibration was mostly in the transverse plane and very little in the longitudinal direction [15,16]. Therefore, it remains unclear how the stiffness variation in the longitudinal direction affects vocal fold vibrations if the anisotropy and longitudinal stiffening was considered. Furthermore, it is also unknown to what extent

the thickness variation in inner layers affects the stiffness variation on vocal fold. Such understanding would be important to estimate the ultimate effect of thickness variation on vocal fold vibrations. Xue et al. [13] utilized an anisotropic vocal fold model to investigate the effect of longitudinal variation of thickness on vocal fold eigenmodes and found that the eigenmodes were insensitive to such variations; yet, it is unclear whether this conclusion still holds when fluid-structure interactions are considered.

To fill the knowledge gap, the present study aimed to utilize a highly sophisticated three-dimensional self-oscillating vocal fold model to investigate the effect of longitudinal variation of inner layer thickness on glottal flow dynamics and vocal fold vibrations. The vocal fold was modeled as a three-layer, transversely isotropic material. The effect of longitudinal stiffening was modeled by applying a large value of longitudinal Young's modulus in the model. The airflow dynamics was modeled by incompressible Navier–Stokes equations. An explicitly coupled immersed-boundary-finite-element method based computational solver was used to simulate flow-structure interaction. The same solver has been used in our previous studies [17–20]. In the present study, the model was advanced by incorporating the inner layer thickness variation. Four vocal fold models of different degrees of variations were generated for the purpose of covering the limit of inter-subject variation. The effect of thickness variation on vocal fold stiffness distribution, glottal flow wave-form, vocal fold vibration pattern, glottal angle, and energy transfer was studied by comparing between the cases. The possible underlying mechanism of the differences was also discussed.

Computational Model

Figure 2(a) shows the three-dimensional geometry of the vocal fold which was generated based on the mathematical model proposed in Ref. [11]. Although it is a simplified geometry, its key features have been carefully designed to be biologically relevant, such as the size and shape of medial surface, anterior–posterior variation, and subglottal angle. The model has been widely used in past studies of vocal fold biomechanics [21–24]. The height of the medial surface of the vocal fold was 0.3 cm, denoted by T in Fig. 2(a).

Fig. 2 (a) The geometry and boundary conditions of the vocal fold. T denotes the height of the medial surface. Points A and B locate at $Y = 3.86$ cm and $Y = 3.66$ cm, respectively, which were used in the calculation of the glottal angles. (b) The varied thickness along the longitudinal direction of the cover and ligament layers in the four cases. (c) and (d) The three-dimensional configurations of the cover and ligament layers of the vocal fold in the baseline case and extreme variation case, respectively. The shapes of the cross section in the vertical direction in the medial surface of the cover and ligament layers were plotted beside the vocal fold with the color of red and black, respectively. (e) The computational domain, geometry of the larynx, vocal fold and vocal tract, and the boundary conditions of the vocal tract; (f) the location and geometry of the ventricle and false vocal folds.

Four vocal fold models with different levels of variation of layer thickness were created. The first model was a uniform thickness model. The thickness of each layer was based on the average value of Hirano's measurement, as shown in Fig. 1, which was 0.33 mm for the cover and 1.11 mm for the ligament. In the second model, the thickness variation was directly based on Hirano's data by using the fitting curves as shown in Fig. 1. In the context below, these two cases are denoted as the baseline model and Hirano model, respectively.

Nevertheless, Hirano's measurement was the average value of five subjects [4]. To take into account the possible extreme conditions of intersubject variation, we created two more cases to have more significant changes of the thickness in the longitudinal direction. The methods for creating the models are briefly described below. A thickness ratio, TR, was defined for each layer, which was computed as the ratio of the largest thickness to smallest thickness along the longitudinal direction. TR_c and TR_l denote the ratio of the cover and ligament, respectively. In the Hirano model, $TR_c = 3.38$ and $TR_l = 2.07$. In the third model, we doubled the values of TR to be $TR_c = 6.77$ and $TR_l = 4.15$. In the fourth model, the values of TR were further increased to be $TR_c = 8.67$ and $TR_l = 4.28$. These two values were chosen because further increasing TR_c and TR_l only resulted in small changes in the largest thickness of each layer. For example, further doubling TR_c and TR_l beyond this point only resulted in less than 10% changes in the largest thickness in the cover and ligament layers. Therefore, the fourth model represented an extreme condition. In the context below, the third and fourth models are denoted as the intermediate variation case and extreme variation case, respectively. The absolute values of the thickness at the five longitudinal positions as in Hirano's measurement (referred to Fig. 1) were computed by using TR_c and TR_l and based on the constraint that the average value remained the same and the assumption that the thickness at the anterior and posterior ends was equal. Figure 2(b) shows the variation of the thickness of the cover and ligament layers in the four models, respectively.

To clearly illustrate the internal structure, Figs. 2(c) and 2(d) show the three-dimensional configurations of the inner layers of the baseline model and the extreme variation model, respectively. The shapes of the cross section in the vertical direction of the medial surface of the cover and ligament layers were plotted beside the vocal folds on the left and right side, respectively. It shows that in the extreme variation model, the cover layer is thickest at the middle and the ligament layer is thickest at the anterior and posterior ends.

The simulations were performed using an in-house immersed-boundary-finite-element method based fluid-structure interaction solver. The numerical algorithm of the solver has been reported in detail in a number of our previous studies [17–20]. A brief introduction is provided here. The glottal aerodynamics was modeled by the incompressible Navier–Stokes equations, and the vocal fold dynamics was modeled by the Navier equation. The coupling between the flow and solid solvers was implemented by tracking the aerodynamic loading on the interface mesh as well as its deformed shape and velocity in a Lagrangian fashion. Vocal fold collision was mimicked by a hard-wall geometric contact model. During vocal fold collision, a small artificial gap (0.2 mm) resolved by two grids was enforced between the two vocal folds to avoid the failure of the flow solver.

Figure 2(e) shows the computational domain, geometry, and boundary conditions of the larynx, vocal fold, and vocal tract. The shape of the supraglottal vocal tract was adopted from Ref. [25]. It consisted of a series of cylinders with cross section areas generated from a neutral area function which was calculated from a collection of vowel area functions of a speaker. This vocal tract model would produce nearly equally spaced formant frequencies [25]. The center line of the supraglottal tract was extracted from an in vivo MRI measurement [26]. Its length was 17.4 cm. The geometries of the ventricle and false vocal folds (Fig. 2(f)) were reconstructed from a thin-slice CT

scan (0.5 mm plane-to-plane resolution) of a 30-year-old male subject [27].

Vocal fold tissues were modeled as linear, viscoelastic, transversely isotropic materials [11,13,28,29]. The material properties used in our model are listed in Table 1. The tissue density (ρ) and Poisson ratios (ν_p and ν_{pz}) were taken from Ref. [30]. The transverse Young's modulus (E_p) and longitudinal shear modulus (G_{pz}) were taken from Ref. [29]. To model the longitudinal stiffening of the vocal fold, a large value of E_z , which was 20 times E_p , was applied. It was shown in Ref. [16] that this ratio would be large enough to suppress the wave in the longitudinal direction. Furthermore, a value of 0 for ν_{pz} was used to decouple the motion in the longitudinal direction and transverse plane. This treatment will further suppress the motion in the longitudinal direction. The values in Table 1 have been tested in a number of previous studies and showed good predictions of vocal fold dynamics [13,19,20,31].

A 1.0 kPa pressure drop was applied between the outlet and the inlet of the vocal tract. Nonslip and nonpenetration boundary conditions were applied on the vocal tract walls. The kinematic viscosity of the air was set to be $1.65 \times 10^{-5} \text{ m}^2/\text{s}$ corresponding to the human body temperature of 37°C . A zero-displacement boundary condition was applied at the anterior, posterior, and lateral surfaces of the vocal fold and other surfaces were free to move. The entire geometry was immersed into a computational domain that was $2.4 \times 14.5 \times 10.8 \text{ cm}$ in dimensions as shown in Fig. 2(e). This domain was discretized by a nonuniform $64 \times 256 \times 192$ Cartesian mesh, with the highest grid density in the intraglottal region. The surface mesh of the vocal tract was discretized by 57,426 triangular elements and each vocal fold was discretized by 28,997 tetrahedron elements. A small time-step of $1 \mu\text{s}$ was used to provide a good temporal resolution while satisfying the CFL constraint. The simulations were carried out on the XSEDE COMET cluster, using 128 processors. The computational expense was about 4600 CPU hours per vibration cycle which equals to 1.5 days per cycle. The grid resolution and the time-step were chosen based on our previous simulation experience with similar configurations [19,20,30–33].

Result and Discussion

Effect of Stiffness Distribution on Vocal Fold Surface. Because the ligament is stiffer than the cover, the spatial variation of layer thickness would affect the stiffness distribution on the vocal fold. Specifically, the thickened cover and thinned ligament at the middle of the vocal fold would reduce the stiffness at the position, and the thinned cover and thickened ligament at the anterior/posterior aspects would increase the stiffness at the position. To examine the extent to which the thickness variation affected the stiffness distribution, a numerical indentation technique was used to measure the stiffness on the vocal fold surface. The indentation was implemented by applying a uniform pressure loading on a small area and then solving the deformation using the finite element solver. The stiffness, defined as the slope of the force-

Table 1 Material properties of the three layers of the vocal fold: ρ is the tissue density; E_p and E_z are the transverse and longitudinal Young's Modulus, respectively; ν_p and ν_{pz} are the in-plane transverse and longitudinal Poisson ratios, respectively; G_{pz} is the longitudinal shear modulus, and η is the damping ratio [16,29,30]

Layer	Material property						
	ρ (g/cm ³)	E_p (kPa)	ν_p	E_z (kPa)	ν_{pz}	G_{pz} (kPa)	η (poise)
Cover	1.043	2.01	0.9	40	0.0	10	5.0
Ligament	1.043	3.31	0.9	66	0.0	40	7.5
Body	1.043	3.99	0.9	80	0.0	20	12.5

Table 2 Voice-quality related quantities calculated from the glottal flow rate and opening wave-forms: F_0 is the fundamental frequency; τ_o is the open quotient; τ_s is the skewness quotient; MFDR is the maximum flow declination rate; Q_{mean} is the mean flow rate; Q_{max} is the maximum flow rate; Gap_{max} is the maximum glottal opening; and k_{ave} is the average stiffness of the vocal fold. The numbers in the round brackets denote the difference with the baseline value (%). The numbers in the square brackets denote the percent value of root-mean-square cyclic oscillation (%).

	Baseline case	Hirano case	Intermediate variation case	Extreme variation case	Physiological range [30]
F_0 (Hz)	170.3 [0.8]	167.9 [0.9] (−1.34)	165.8 [0.9] (−2.61)	168.7 [1.0] (−0.89)	60–250
τ_o	0.537 [1.1]	0.539 [1.3] (0.26)	0.535 [1.6] (−0.36)	0.544 [1.0] (1.16)	0.4–0.7
τ_s	2.29 [2.5]	2.48 [3.9] (8.05)	2.30 [3.0] (0.37)	2.38 [5.3] (3.94)	1.1–3
MFDR (m^3/s^2)	0.479 [2.7]	0.468 [4.9] (−2.12)	0.473 [2.0] (−1.12)	0.462 [3.5] (−3.41)	—
Q_{mean} (mL/s)	159.8 [1.6]	154.7 [0.5] (−3.2)	154.7 [0.8] (−3.2)	153.8 [1.5] (−3.7)	110–220
Q_{max} (mL/s)	333.9 [0.8]	323.1 [2.8] (−3.5)	326.9 [0.7] (−2.4)	315.1 [2.6] (−5.9)	200–350
Gap_{max} (mm)	0.98 [1.2]	0.978 [5.3] (−0.2)	1.023 [1.8] (4.4)	1.001 [3.3] (2.14)	—
k_{ave} (kPa · cm)	1.31	1.27 (−3.0)	1.24 (−5.1)	1.37 (5.0)	—

displacement curve, can be calculated as $k = PA/\Delta x$, where k is the stiffness, P is the pressure loading, A is the area, and Δx is the maximum deformation. The details about the numerical indentation method can be found in Ref. [34]. To obtain the distribution of the stiffness, the medial surface of the vocal fold was evenly divided into 21 sections with seven sections in the longitudinal direction and three sections in the vertical direction (shown in Fig. 3). The portion that is close to the two ends was excluded since they were constrained by the fixed boundary condition and would barely vibrate. The numerical indentation was applied at each section. Figure 3 shows the stiffness distribution along the longitudinal direction on the medial surface of the four vocal fold models by averaging the values in the vertical direction. It reflects

that, for all the vocal fold models, the stiffness was lowest at the center and highest at the posterior end. It needs to be pointed out that stiffness is a function of many properties including the material properties, material orientation, geometric dimensions, type of constraint, and loading direction and position. Therefore, even though the layers were uniform in the baseline model, the stiffness was still increased toward the anterior/posterior end and that was the effect of fixed boundary condition. Generally, a larger thickness variation resulted in a larger stiffness variation. Such effect was most prominent when comparing the baseline model and Hirano model. The thickness variation has resulted in a much lower stiffness in the middle and higher stiffness toward the anterior/posterior ends. It was also interesting to notice that further increasing the thickness variation in the intermediate variation model and extreme variation model only resulted in a small change in the stiffness at most places of the vocal fold except near the anterior/posterior ends. That means the stiffness distribution became insensitive to the thickness variation once the thickness variation level exceeded that in the Hirano model. Quantitatively, by using the values in the baseline model as the normalized values, the stiffness decreased by 16%, 21%, and 24% at the middle, increased by 18%, 12%, and 47% near the anterior end, and increased by 5%, 10%, and 29% near the posterior end for the Hirano model, intermediate variation model, and extreme variation model, respectively. The average stiffness over the entire medial surface was computed by averaging the stiffness values in the 21 sections. Interestingly, it was found that the value only changed by −3%, −5%, and +5% in the Hirano model, intermediate variation model, and extreme variation model, respectively. Considering that the same average thickness was kept for each layer among the cases, it implied that the average stiffness was highly correlated with the average thickness of the inner layers.

Fig. 3 The stiffness distributions along the longitudinal direction at the medial surface of the four vocal fold models. The subfigure illustrates the sections used in the numerical indentation.

Effect on the Wave-Forms of the Glottal Flowrate and Opening Size. The time history plot of the glottal flow rate and glottal opening size of the baseline case was shown in Fig. 4(a).

Fig. 4 (a) The time history of the glottal flow rate and glottal opening of the baseline case, and (b) the phase-averaged flow rate and glottal opening for the four cases

And the phase-averaged flow rate and opening size for the four cases was shown in Fig. 4(b). The opening size was defined as the minimum distance between the two vocal folds across the vertical direction in the midcoronal plane. Based on the waveforms of the flow rate and opening size, several voice-quality related quantities were calculated for the four cases and listed in Table 2. These include the fundamental frequency (F_0), open quotient (τ_o), skewness quotient (τ_s), maximum flow declination rate (MFDR), maximum flow rate ($Q_{\max}$), mean flow rate (Q_{mean}), and maximum glottal opening ($\text{Gap}_{\max}$). τ_o was defined as the duration of the open glottis divided by the period of the cycle. τ_s was defined as the duration of flow acceleration divided by the duration of flow declination. Both parameters were calculated based on the waveform of the glottal flow rate. MFDR was obtained by calculating the time derivative of the flow rate during the closing phase of the glottis. It should be pointed out that these quantities were computed by using the phase-averaged flow rate and opening size which has eliminated the effect of cyclic variation.

To compare between the cases, the relative differences of the parameters by using the values in the baseline case as the normalized values were computed. They are shown in the round brackets in Table 2. Moreover, the percent values of cyclic variation of some of the parameters, which were computed as the root-mean-square of the variation of each cycle from the mean value, were also computed and listed in the square brackets. It was found that the differences with the baseline case in these parameters were generally below 5% except that τ_s in the Hirano model increased by 8% and $Q_{\max}$ in the extreme variation case decreased by 5.9%. The cyclic variations were generally at the same level. Therefore, the thickness variations did not have a significant effect on the glottal flow and opening size waveforms.

It is generally assumed that, with the reduced stiffness at the middle of the vocal fold, the vibration amplitude and flow rate would increase because the middle area is where the largest vibration occurs. However, in our simulations, although the stiffness was reduced by 16%–24% at the middle in the cases, the vibration amplitude and flow rate remained nearly the same as the baseline case. Considering that the average stiffness remained nearly the same among the cases, our simulation results implied that the vibration amplitude and flow rate were determined by the average stiffness, not the local stiffness. This result contradicted with the conclusion of a previous study which applied modulus gradients in the longitudinal direction in an isotropic vocal fold model and found that the stiffness gradients affected the fundamental

frequency and flow rate [9]. However, as aforementioned in the introduction, the model employed the isotropic material assumption and did not incorporate the effect of longitudinal stiffening of vocal fold, and therefore, created a strong wave motion in the longitudinal direction. This artificial wave motion would affect the motion in the transverse plane and further affect the fundamental frequency and flow rate. Furthermore, it was unclear if the average stiffness was maintained among the cases in Ref. [9]. Therefore, it was unclear if the observed effect is due to the stiffness gradient or the change of the average stiffness.

Effect on Vocal Fold Vibration Pattern. While the four cases showed nearly the same vibration amplitude, it would be of interest to examine their vibration patterns. When the vocal folds vibrate, a mucosal wave forms and propagates in the cover layer. This wave generates an inferior–superior phase difference in the motion, creating an alternating convergent–divergent glottal shape, which is a key mechanism for sustained energy transfer from the air flow to vocal folds. Figure 5 plots the midcoronal profile of the vocal folds at four time instants during one vibration cycle for the baseline case and the extreme variation case. The time instant associated with each subfigure is indicated as a black dot on the flow rate plot shown at the right-bottom. It can be seen that the glottis showed alternating convergent–divergent shapes in both cases. At instant (a), the glottis was about to open with a very clear convergent shape in the inferior–superior direction. At instant (b), the glottis reached its maximum opening, forming a nearly straight channel. Due to flow inertia, the glottal flow was still increasing although the glottis had already started to close. At instant (c), the glottis was closing with a very clear divergent shape, and the glottal flow was decreasing. At instant (d), the glottis was fully closed (with artificial gap). It is also important to see that the profiles from the two cases nearly overlapped each other, indicating the high similarity of the vibration pattern.

To have a quantitative comparison of the vibration pattern between the cases, the technique of proper orthogonal decomposition was applied to extract the principle modes of the vibration [20,35]. As the vibration was nearly symmetric about the centerline, only the left vocal fold was analyzed. Figures 6(a) and 6(b) show the three-dimensional shape as well as the midcoronal profile of the vocal fold of the two most energetic modes of the baseline case. The two modes together captured 93% of the total kinetic energy, 82% and 11% in each mode, respectively. Mode 1

Fig. 5 The midcoronal profiles of the vocal folds at four time instants during one vibration cycle in the baseline and extreme variation cases. The corresponding time instant is indicated as a black dot on the flow rate plot shown at the right-bottom of each subfigure.

Fig. 6 The two most energetic modes of the baseline case: (a) Mode 1 and (b) Mode 2. In each subfigure, the left side is the three-dimensional shape and the right side is the midcoronal profile of the vocal fold.

Fig. 7 The phase-averaged glottal angle variation at the three coronal planes for the four cases. The position of each coronal plane is denoted at the top-right corner of each figure.

was mostly an in-phase lateral motion and Mode 2 was an out-of-phase lateral motion. The same modal shapes were observed in other cases. The energy associated with the two modes was 80% and 12% in the Hirano model, 77% and 13% in intermediate variation case, 78% and 13% in extreme variation case, respectively. To precisely quantify the similarity of the modal shapes, the dot-products of the unit vectors of the two corresponding modes between the baseline case and the other three cases were computed. The value of one indicated an exact match of the modal shape, and the value of zero indicated complete orthogonality. The results showed that the dot-products of the two corresponding modes between the baseline case and other cases were all above 0.98, indicating nearly the same vibration patterns between the cases.

Effect on Glottal Angles. Figure 7 shows the phase-averaged variation of the glottal angle at three coronal planes for the four cases. Because the vocal folds vibrated symmetrically about the midsagittal plane, the glottal angle was measured between the right vocal fold and the midsagittal plane. It was calculated by assuming a straight line between two points on the vocal fold that

were initially at $Y = 3.86$ and $Y = 3.66$ cm (indicated in Fig. 2(a)). A positive angle corresponded to a convergent shape and a negative angle corresponded to a divergent shape. Two common features were observed for all the cases. First, the glottal angle decreased from the midcoronal plane to the anterior and posterior ends. It is easy to understand because the vocal folds were fixed at the anterior and posterior ends so that the vibration was gradually constrained toward them. Second, at each plane, the maximum convergent angle was larger than the maximum divergent angle (absolute value). At the midcoronal plane (Fig. 7(a)), the maximum convergent angles were 6.57 ± 0.11 deg, 7.62 ± 0.50 deg, 8.45 ± 0.25 deg, and 8.79 ± 0.21 deg in the baseline, Hirano, intermediate variation, and extreme variation cases, respectively, and the maximum divergent angles were 3.05 ± 0.16 deg, 4.03 ± 0.52 deg, 4.74 ± 0.36 deg, and 4.24 ± 0.81 deg, respectively. The second number denotes the root-mean-square value of the cyclic variation. This feature may be related to the slow opening and fast closing of the vocal folds so that there was less time for developing the angle during closing.

Differences between these cases were also observed. In Fig. 7(a) which is for the midcoronal plane, the baseline case had the smallest maximum angles in both the convergent and

Fig. 8 The phase-averaged maximum glottal angle distribution in the longitudinal direction: (a) convergent angle and (b) divergent angle

divergent shapes. A higher level of thickness variation generated larger maximum angles. However, the difference between the cases gradually vanished toward the anterior end, as shown in Figs. 7(b) and 7(c). To further illustrate this difference, Figs. 8(a) and 8(b) show the maximum convergent and divergent angles at different longitudinal positions for the cases. It was found that the thickness variations generated larger maximum convergent and divergent angles in the middle of the vocal fold and smaller angles near the anterior and posterior ends. Specifically, Fig. 8(a) shows that the thickness variations had a large effect on the convergent angles at the middle of the vocal fold and small effect near the anterior and posterior ends. The effect at the middle of the vocal fold was monotonic that a higher level of thickness variation generated larger angles. Interestingly, Fig. 8(b) shows a nonmonotonic trend that the intermediate variation case generated the largest maximum divergent angle in the middle, while the extreme variation case generated the smallest maximum divergent angle near the anterior and posterior ends. Also, the intermediate variation case had a larger maximum divergent angle than the Hirano model near the anterior end. A closer comparison with the stiffness values in Fig. 3 revealed that this nonmonotonic trend was highly correlated to the stiffness distributions. It was observed in Fig. 3 that the intermediate variation case had the smallest stiffness at the longitudinal position between 0.65 and 0.8 and smaller stiffness than the Hirano model near the anterior end. It was consistent with the trend of divergent angles at these positions. It was noticed that the intermediate variation case did not have the smallest stiffness at the middle but had the largest divergent angles there. It could be the effect of the adjacent tissues at the longitudinal position between 0.65 and 0.8 which had much larger angles than other cases. The above observations implied that the glottal angles were largely affected by the local stiffness. Such relationship was more prominent in the divergent angles which might be due to that glottal closing is primarily driven by the elastic recoil force inside the vocal folds which are directly related to the stiffness.

It needs to be pointed out that the maximum convergent angles increased by up to 34% and the maximum divergent angles increased by up to 55% among the thickness variation cases by comparing to the baseline case. However, the absolute changes were small which were less than 2.3 deg for the convergent angle and 1.8 deg for the divergent angle. Considering that the angle was calculated for half of the glottis, the absolute change would be less than 4.6 deg and 3.6 deg for convergent and divergent angles, respectively, if the full angle between the two vocal folds was used. This small change in the glottal angle did not result in noticeable difference in the vibration patterns.

Effect on Energy Transfer. Figure 9(a) shows the phase-averaged power transfer from the air flow to the vocal fold during one vibration cycle for the four cases. Figure 9(b) shows the phase-averaged glottal opening size. The power was calculated by multiplying the flow pressure with the normal components of the velocity vectors and integrating over the entire vocal fold surface. The contribution of the viscous force to the power was neglected since it is usually two orders of magnitude smaller than the pressure contribution [36]. It was interesting to see that, for all these cases, the power was positive at the very early opening phase and most of the closing phase. During other times, it was negative. It suggested that the aerodynamic pressure facilitated the vocal fold motion during the early opening phase and most of the closing phase, and retarded its motion at other times.

The cyclic net energy transfer to the vocal fold was calculated by integrating the power over one vibration cycle. It was $28.56 \pm 1.47 \mu\text{J}$, $26.21 \pm 1.73 \mu\text{J}$, $27.50 \pm 0.84 \mu\text{J}$, and $24.15 \pm 0.95 \mu\text{J}$ for the baseline, Hirano, intermediate variation and extreme variation cases, respectively. The second number denotes the root-mean-square variation between cycles. Hence, the cyclic net energy transfer decreased by -8.2% , -3.7% , and

Fig. 9 (a) The phase-averaged time history of the power transferred from the air flow to one vocal fold in the four cases and (b) the phase-averaged glottal opening size. The time instants of MFDR are represented by black dots.

Fig. 10 The phase-averaged intraglottal pressure along the centerline at the time instants of the positive power peak observed in Fig. 9 for the four cases

–15.4% in the Hirano model, intermediate variation model, and extreme variation model, respectively, compared to the baseline model. The cyclic variation was 5.1%, 6.6%, 3.0%, and 3.9% of the mean values, in the baseline model, Hirano model, intermediate variation model, and extreme variation model, respectively. Figure 9 reflected that the effect on the cyclic net energy transfer might be associated with the positive peak of the power that occurred when the glottis was about to close. This peak contributed a significant amount of positive energy to the vocal fold. The changing trend of the peak among the cases was in accordance with the changing trend of the cyclic net energy transfer.

To explore the reason of the changes of the power peak among the cases, Fig. 10 plots the phase-averaged flow pressure along the centerline of the glottis at the time instant when the positive power peak occurred for all the cases. It shows that, at this time instant, the flow pressure dropped to a negative value around –1––1.5 kPa inside the glottis in all the cases. The baseline case had the lowest negative pressure, followed by the intermediate variation case, extreme variation case, and the Hirano case in the ordered sequence. This low negative pressure generated a larger vacuum force to pull the vocal folds to close. Therefore, a lower negative pressure would contribute to higher power peak. Such sequence of intraglottal pressure is generally in accordance with the sequence of the power peak as shown in Fig. 9 except that the Hirano case had the higher intraglottal pressure than the extreme variation case. It should be noticed that, other than the intraglottal pressure, the vocal fold velocity, face normal direction, and the integration in time would also affect the energy consumption during vibration. This might explain that though the Hirano case had the highest intraglottal pressure, the energy consumption was not the lowest. However, the trend that the longitudinal thickness variation would increase the intraglottal pressure which would further decrease the energy needed to sustain the vocal fold vibration was clear.

Then, it became interesting to explore the mechanism responsible for the lowest negative pressure in the baseline case. There are two primary mechanisms responsible for the negative intraglottal pressure during the closing phase. One is the steady effect that is related to Bernoulli's effect in which the pressure drop is proportional to the square of the flow rate. But such effect will be weak at the time instant when the flow rate was very low, such as the condition in the current cases. The second mechanism for the

negative intraglottal pressure would be the unsteady effect which is related to the flow inductance. The pressure difference caused by the flow inductance in a tube can be calculated as $\Delta p = I(dQ/dt)$, where I is the flow inductance characterized by the density of the fluid, length, and cross section area of the tube, and Q is the volumetric flow-rate. In contrast to Bernoulli's effect which is directly related to the flow-rate, the flow inductance caused pressure change is related to the time derivative of the flow rate. During the closing phase of the glottis, the deceleration of the flow caused the negative time derivative of the flow rate, and therefore, the negative flow pressure inside the glottis. Figure 9 also denotes the time instants of the MFDR in the opening size plot for all the cases. It was found that the time instants of the positive power peak and MFDR were very close. Therefore, the very low intraglottal pressure observed in Fig. 10 was primarily caused by the strong flow inductance effect due to the MFDR. Table 2 listed values of the MFDR for the cases. The baseline case had the highest MFDR value. Therefore, its intraglottal pressure was able to drop to a lowest value. That further explained the highest positive power peak in the baseline case.

Conclusion

This study utilized a three-dimensional, fluid-structure interaction computational model to investigate the effect of longitudinal variation of vocal fold inner layer thickness on vocal fold vibration. Four cases, one with the constant layer thickness in the longitudinal direction and three with different degrees of longitudinal variation, were studied and compared. In the extreme variation case, the thickest part of the cover/ligament layer can be 8.67/4.28 times the thinnest part. Such variation has caused 24% reduction in the stiffness at the middle of the vocal fold and 47% and 29% increase in the stiffness at the anterior and posterior ends, respectively. The main observations and discussions are summarized as below:

- (1) The variation of inner layer thickness in the longitudinal direction as well as the resulted variation of stiffness distribution on the vocal fold did not affect the flow rate and vibration amplitude. The results implied that the flow rate and the vibration amplitude were highly related to the average stiffness over the vocal fold medial surface rather than the stiffness at the middle of the vocal fold. In our models, the stiffness at the middle of the vocal fold decreased up to 24%; however, the changes in the average stiffness were only within 5%. The changes in the flow rate and vibration amplitude were within 6%.
- (2) The maximum glottal angles were increased at the middle of the vocal fold and reduced at the anterior/posterior ends in the thickness varied cases. The results implied that the maximum convergent and divergent glottal angles along the longitudinal direction were largely determined by the local stiffness at the longitudinal positions. Such a relationship was more prominent in the divergent angles maybe because glottal closing is primarily driven by the elastic recoil force inside the vocal folds which are directly related to the stiffness.
- (3) The thickness variations had little effect on the vocal fold vibration patterns. The proper orthogonal decomposition analysis showed nearly the same principle modes and energy distributions between the modes for all the models.
- (4) The energy analysis revealed that a key contribution to the positive net energy transfer to the vocal fold was a positive power peak when the glottis was about to close. This positive power peak was primarily due to the negative intraglottal pressure caused by flow inductance which was related to MFDR. The thickness variations in the longitudinal direction were found to help decrease the energy needed in the sustained vibration due to the higher intraglottal pressures which were related with the smaller MFDR.

It is useful to point out that our results were based on the models with specific material properties. Vocal fold material properties vary from individual to individual depending on factors such as gender, race, age, and health. These variations are likely to affect the quantitative conclusions. For example, increasing the difference of Young's modulus between the cover and ligament layers will increase the variation of the stiffness along the longitudinal direction in the models, and this will affect the quantities reported in the present study. There has been more experimental work recently to provide more comprehensive material measurements, including the anisotropic and nonhomogeneous aspects. Literature data were summarized in Refs. [37–40]. These data can provide new insight in modeling vocal fold tissues.

Acknowledgment

The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIDCD or the National Institutes of Health (NIH).

Funding Data

- National Institute on Deafness and Other Communication Disorders (NIDCD) (Grant Number 1R03DC014562).
- Numerical simulation used the Extreme Science and Engineering Discovery Environment (XSEDE) (allocation award number TG-BIO150055).

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